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Critical Heat Flux in Inclined Rectangular Narrow Long Channel

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Abstract – *In the TMI-2 accident, the lower part of the reactor pressure vessel had been overheated and then rather rapidly cooled down, as was later identified in a vessel investigation project. This accounted for the possibility of gap cooling feasibility. For this reason, several investigations were performed to determine the critical heat flux (CHF) from the standpoint of in-vessel retention. The experiments are conducted to investigate the general boiling phenomena, and the triggering mechanism for the CHF in a narrow gap using a 5×105 mm^2 crevice type heater assembly and de-mineralized water. The test parameters include the gap size of 5 mm, and the surface orientation angles from the downward facing position (180^o) to the vertical position (90^o). The orientation angle affects the bubble layer and escape from the narrow gap. The CHF is less than that in a shorter channel, compared with the previous experiments having a heated length of 35 mm in the copper test section.*

I. INTRODUCTION

In recent years, the effects of surface orientation and gap size on the pool boiling heat transfer and the critical heat flux (CHF) have received increasing attention because of the potential benefits pool boiling may bring to a number of applications including cooling of electronic and power devices, heat treatment of metallic parts, and cooling of the superconductor coils. In view of accident management for a high power nuclear reactor, it is essential to accurately predict the quantitative magnitude of CHF. In the Three-Mile Island Unit 2 (TMI-2) accident, the lower part of the reactor vessel was overheated but then rather rapidly cooled down.[1,2] This accounted for the possibility of cooling in the narrow gap on the order of millimeters and centimeters that may have been formed between the solidified core debris and the reactor vessel lower head. Post-test analyses, completed as part of the TMI-2 Vessel Investigation Project[3] suggested the presence of the core material-to-vessel gaps. For this reason, additional data are needed to quantify CHF in narrow gaps and gain insights about the potential for in-vessel retention (IVR). The CHF test sections need to address key features of the engineering device to simulate the IVR environment. In particular, major issues are centered about geometric parameters affecting the CHF, such as the surface orientation and the gap size. Hence, research on the CHF during pool boiling in confined channels is important as a fundamental study of the CHF phenomenon as well as for its application to industrial problems. In this case, owing to the complexity of flow mode, many investigators have suffered from difficulties in interpreting the heat transfer phenomena in highly confined channels. Additionally, the CHF triggering mechanism still defies full understanding due primarily to the effect of surface orientation. A series of fundamental studies were conducted to develop engineering correlations taking account of the combined effect of the heated surface orientation and gap size using the apparatus GAMMA 1D (Gap Apparatus Mitigating Melt Attack One Dimensional).

II. BACKGROUND

Previous studies regarding the surface orientation and gap size effect on the pool boiling CHF have primarily been quantitative in nature. Several investigators have attempted to correlate the orientation effect on the CHF or to provide physical insight into the problem. Several other researchers made contributions in understanding of the CHF phenomena by performing their experiments in the narrow gap structured channel and correlating their CHF data. A few authors have derived generalized correlations that are applicable to the CHF data for many kinds of fluids. Some critical studies available in the literature are now presented concerning the surface orientation and gap size effect on the CHF.

II.A. Surface Orientation Effect

Ishigai et al.[4] and Githinji and Sabersky[5], among the first investigators to explore the effect of orientation on the pool boiling CHF, noted that the CHF decreases drastically when the heated surface is oriented in the horizontal, downward facing position (180^o) because the vapor accumulates and prevents liquid access to the heated surface. Numerous other pool boiling CHF studies examined the orientation effect, and in general these investigations found that the CHF decreases as orientation changes from upward facing horizontal (0^o) to vertical (90^o) to downward facing horizontal (180^o).

Vishnev[6] was the first to correlate the effect of orientation on the pool boiling CHF, and his correlation is still the most widely utilized:

$$\frac{q_c}{q_{c,0^o}} = \frac{(190-\theta)^{0.5}}{190^{0.5}} \tag{1}$$

Nishikawa et al.[7] performed nucleate boiling tests with a copper plate with the angles varying from 0°(upward) to 175°(inclined downward). They carried out the experiments for the saturated pool boiling of water at atmospheric pressure to clarify the effect of the surface configuration on nucleate boiling heat transfer. They reported that the effect of the surface configuration is remarkable at low heat fluxes and the heat transfer coefficient becomes large as the inclination angle is increased in this case, while no marked effect is observed at high heat fluxes. In particular, they considered two mechanisms concerning heat transfer from the inclined surface facing downwards. One is the sensible heat transport due to compulsory removal of the thermal layer by the elongated bubble rising along the surface. The other is the latent heat transport due to evaporation of the thin liquid film beneath the elongated bubble. Their analytical model of these mechanisms indicated that the heat transfer from the inclined surface facing downwards is controlled mainly by the latent heat transport.

El-Genk and Guo[8] carried out the experiments for the effect of surface inclination on heat transfer in the different boiling regimes with a copper disk having a thickness of 12.8 mm and a diameter of 50.8 mm in a pool of saturated water at near atmospheric pressure. They reported several experimental results. First, the CHF and minimum film boiling heat flux, as well as the corresponding wall superheat, increase with increasing angle of inclination. Second, in the nucleate boiling region, increasing surface inclination results in a decrease in heat transfer rate at lower wall superheats. At higher wall superheats the nucleate boiling heat transfer coefficient decreases slightly with the inclination angle. Third, the CHF and minimum film boiling heat flux for the downward facing position are significantly lower than those for other inclination angles. The quenching time depends strongly on the angle of inclination. The quenching time for the downward facing surface is about six times that for 5° inclination and 23 times that for 90° inclination. El-Genk and Guo[9] later developed the following CHF correlation:

$$q_{c,f} = C_{CHF,f}(\theta)\rho_g h_{fg}\left[\frac{\sigma(\rho_f-\rho_g)g_c}{\rho_g{}^2}\right]^{1/4} \tag{2}$$

Chang and You[10] also carried out the experiments to understand the effect of surface orientation on the saturated FC-72 pool boiling performance of flush-mounted square heaters. They reported the interesting results that higher inclination angles provided better heat transfer in the nucleate boiling regime, as the plain surface was rotated from θ=0^o (downward) to 90^o (vertical). They suggested that, however, as the orientation angle was further increased from θ=90^o (vertical) to 180^o (upward), nucleate boiling heat transfer noticeably decreased at higher heat fluxes. They claimed that this reduction in boiling heat transfer contrasts with previous researchers' observations at the partially developed nucleate boiling region. Finally, they correlated the normalized CHF data at different orientations angle using the empirical derivation:

$$\frac{q_c}{q_{c,0^o}} = 1-1.2\times10^{-4}\theta\tan(0.414\theta)-0.122\sin(0.318\theta) \tag{3}$$

Brusstar and Merte[11] and Brusstar et al.[12] developed an empirical CHF model for pool and flow boiling. They used a copper plate to investigate the surface orientation effect in R-113 pool. El-Genk and Guo[9] avoided the use of a single universal correlation for all fluids. Instead, they derived separate correlations for three fluids based on data from the literature:

$$\frac{q_c}{q_{c,0^o}} = \begin{cases} 1.0 & 0^o < \theta \le 90^o \\ (\sin\theta)^{12} & 90^o \le \theta < 180^o \end{cases} \tag{4}$$

Howard et al.[13] performed the saturated pool boiling experiments and flow visualization studies at various surface orientations to ascertain the CHF triggering mechanism associated with each orientation. Based on the vapor behavior observed just prior to the CHF, they analyzed that surface orientations can be divided into three regions: upward facing (0-60°), near vertical (60-165°) and downward facing (>165°). In the upward facing region, the buoyancy forces remove the vapor vertically off the heater surface. The near-vertical region is characterized by a wavy liquid-vapor interface that sweeps along the heater surface. In the downward facing region, the vapor repeatedly stratifies on the surface, greatly decreasing CHF. They concluded that the differences between the observed vapor behaviors within the three regions indicate that a single overall pool boiling CHF model cannot possibly account for all the observed orientation effects, but instead three different models should be developed for the three regions.

II.B. Gap Size Effect

Katto and Yokoya[14] performed experiments on boiling of saturated water at atmospheric pressure in a space bounded by two horizontal co-axial disks, with lower-disk heating, but no correlations of the CHF data were presented.

Jensen et al.[15] performed the CHF tests for natural convection boiling of saturated water at atmospheric pressure in horizontal annular geometries with inside-rod heating. They presented a generalized equation correlating their own data of water together with the data of R-113 obtained by others. Their correlation was derived on the basis of the Reynolds number referenced to viscous flow of vapor in the confined space. The effect of the gravitational acceleration g_c was not taken into account:

$$\left[\frac{q_c(d/s)}{2h_{fg}}\right]\left(\frac{d}{2s}\right)\left(\frac{\rho_f-\rho_g}{\rho_g}\right)^{0.78} = 2.994\times10^5\left(\frac{s}{l}\right)^{-0.213} \tag{5}$$

On the other hand, Smirnov et al.[16] and Smirnov[17] measured the CHF q_c for saturated boiling of water at 0.5~5 bar and that of ethyl alcohol at 1 bar in a horizontal rectangular slot of length b and clearance s. On the other hand, q_c* is the CHF in ordinary pool boiling on an open heated surface. They made the empirical correlation referenced to the ordinary pool boiling on an open heated surface:

$$q_c = q_c^* \frac{1}{\sqrt{\left(1 + C_3 \frac{\rho_g}{\rho_f}\left(\frac{b}{s}\right)^3\right)}} \tag{6}$$

Katto et al.[18] conducted the CHF experiments in gap boiling at atmospheric pressure for disk diameters of d=10 and 20 mm, the distance between the parallel disks s in a range of d/s=0~120, and four different fluids as water, R-113, ethyl alcohol and benzene. They correlated data with a generalized equation that has an uncertainty of about ±15% from the experiment data:

$$\frac{q_c/\rho_g h_{fg}}{\sqrt[4]{\frac{\sigma g_c(\rho_f-\rho_g)}{\rho_g^2}}} = \frac{0.18}{1+0.00918\left(\frac{\rho_g}{\rho_f}\right)^{0.14}\sqrt{\left(\frac{g_c(\rho_f-\rho_g)d^2}{\sigma}\right)}\frac{d}{s}} \tag{7}$$

Monde et al.[19] performed the CHF experiments with a copper plate forming the vertical rectangular channel with gap sizes varying from 0.45 to 7.0 mm corresponding l/s less than 120 in four test liquids as water, ethanol, R-113 and benzene. As a consequence of the experiment, they developed a generalized correlation of the CHF data that agree with the experimental data within ±20%:

$$\frac{q_c/\rho_g h_{fg}}{\sqrt[4]{\frac{\sigma g_c(\rho_f-\rho_g)}{\rho_g^2}}} = \frac{0.16}{1+6.7\times10^{-4}\left(\frac{\rho_f}{\rho_g}\right)^{0.6}\left(\frac{l}{s}\right)} \tag{8}$$

Chang and Yao[20] performed CHF experiments with annular vertical tube with closed bottoms in an R-113 pool. They used the annular tube having gap sizes of 0.32, 0.8 and 2.58 mm. They found that the CHF in narrow gaps was much smaller than in the pool boiling. They correlated the CHF prediction model pursuant to the counter-current flow limitation:

$$\frac{q_c}{\rho_g h_{fg}}\sqrt{\frac{\rho_g}{gd\,\Delta\rho}} = \frac{0.38}{\left(1+\sqrt[4]{\rho_g/\rho_f}\right)^2(l/s)} \tag{9}$$

Chyu[21] proposed a one-dimensional two-phase flow model in a narrow vertical channel assuming that saturated liquid enters the horizontal annulus channel at the bottom, and is vaporized by the heating wall while ascending due to buoyancy:

$$q_c = \rho_g h_{fg}\left(\frac{s}{l}\right)\left[\frac{gl\sin\theta\left[\left(\rho_f/\rho_g\right)-2\right]}{1+fl/2s}\right]^{1/2} \quad (10)$$

He obtained the friction factor from the experimental data:

$$f = 0.13\left(\frac{\rho_f-\rho_g}{\rho_g}\right)^{1/2} Bo^{1.3} \quad (11)$$

where

$$Bo = s\left[\frac{g}{\sigma}\left(\rho_f-\rho_g\right)\right]^{1/2} \quad (12)$$

Later, Kim et al.[22] modified Chyu's correlation by adopting the new friction factor correlation considering the vertical and inclined channels. They suggested the new friction factor with an RMS error of 5.87%:

$$f = 0.0041 \times s^{(3.66\log s - 0.94)} \quad (13)$$

Kim and Suh[23] performed the CHF experiments with a copper plate in rectangular channel at atmospheric pressure with the de-mineralized water within the surface orientation from vertical (90^o) to downward facing (180^o) position. The gap sizes were 1, 2, 5 and 10 mm. They developed a generalized correlation that agreed with the experimental data within ± 20%:

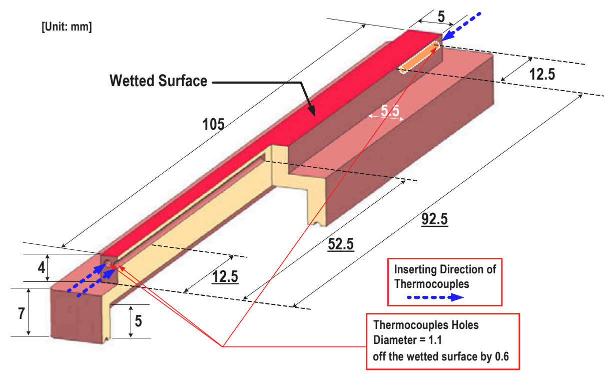
$$\frac{q_c/\rho_g h_{fg}}{\sqrt[4]{\sigma g\sin(\theta)\left(\rho_f-\rho_g\right)/\rho_g^2}} = \frac{0.17}{1+6.8\times10^{-4}\cdot\left(\rho_f/\rho_g\right)^{0.62}\left(D_h/s\right)} \quad (14)$$

III. EXPERIMENT

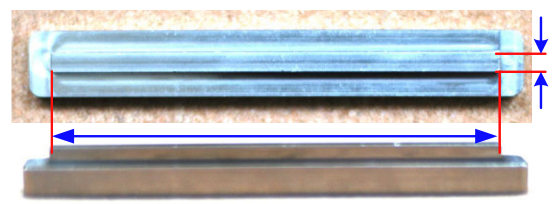
III.A. Experimental Apparatus

In the GAMMA 1D apparatus, heat was supplied by DC power of 6 kW with a DC output voltage of 300 V and a current of 20 A. The quantitative information about the output voltage, ampere and watt generated on the test heater material was exported by the RS-232C to an IBM PC. A quasi-direct heating method was adopted to generate sufficient heat flux in this experiment.

The heater assembly was fabricated utilizing the copper block test heater and the film resistor. A copper block with the wetted surface of 5×105 mm^2 was used. Thin film resistors having a resistance of 20 were affixed into the copper block heater to measure the CHF. This also facilitated obtaining the required heat flux by applying a current less than 10 A. A schematic diagram of the copper block heater is illustrated in Figure 1(a), in which the chromel-alumel (K-type) thermocouples were inserted into the holes 0.6 mm below the wetted surface to measure the temperature behavior on the wetted surface. For the test heater used in this study, three K-type thermocouples were inserted into depths of 12.5, 52.5 and 92.5 mm, respectively. Figure 1(b) shows that the test heater was slightly coated with nickel to prevent the test heater from getting oxidized.



(a) schematic diagram



(b) pictures of top and side views

Fig. 1. GAMMA 1D test heater block

Regarding the device holding the heater assembly, stainless steel housing was designed to ensure efficient insulation of the heated section, as demonstrated in Figure 2. The inner surface of the housing was polished smoothly such that the housing could be evacuated. This allowed an efficient insulation of the heated section. Hence, as part of forming a vacuum, an O-ring frame was grooved in the upper part of the housing, and a link of O-ring was sealed on the housing with vacuum grease.

After sticking the copper block heater into the housing, a flexible stainless steel tube was attached to the flange located at the bottom of the housing and a vacuum pump loaded about 10^{-4} torr, which can considerably reduce the heat loss from the bottom of the copper block heater. The conduction heat loss between copper block and housing can be reduced in attaching the high temperature epoxy around the side part of the housing. Pyrex glass was imbedded into the edge of the housing and designed to precisely maintain the gap size of 5 mm, and to visualize the test apparatus having a narrow rectangular channel, as shown in Figure 2.

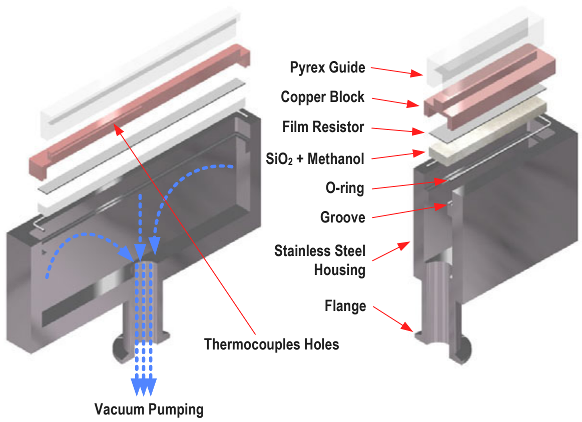


Fig. 2. Test heater with vacuum housing

III.B. Experimental Condition

The CHF tests were performed in the atmosphere water pool surrounded by a vacuum tank, as schematically shown in Figure 3.

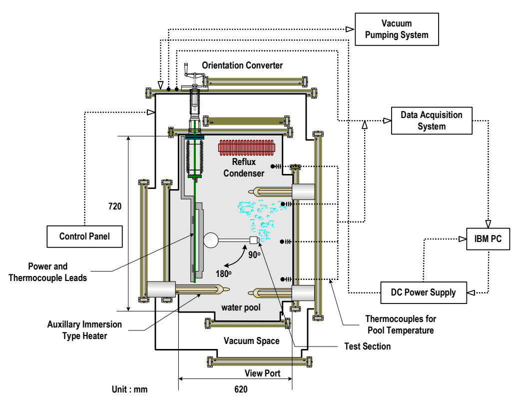
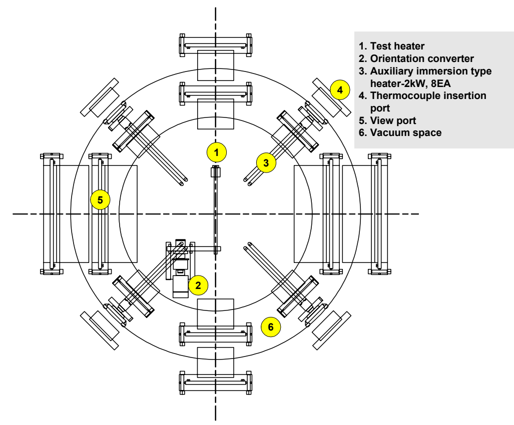
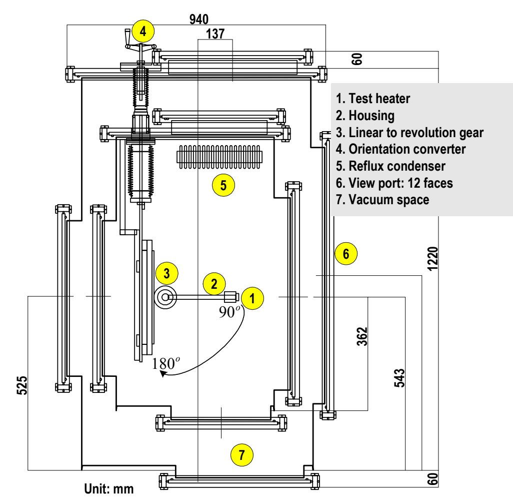


Fig. 3. GAMMA 1D test apparatus

In the same way as the housing, the water pool shown in Figures 4(a) and 4(b) was surrounded by a vacuum for insulation. Additionally, this functions to sustain a steady thermal hydraulic state of water at atmospheric pressure. Eight immersion-type heaters having the electric capacity of 2 kW were homogeneously inserted into the test pool to pre-heat the de-mineralized water in the test pool up to the saturated state. A reflux condenser was equipped in the test pool itself to maintain the pressure in the water pool. After installation was completed for the GAMMA 1D apparatus, the CHF was measured in the narrow channel of the crevice type copper heater block at preset inclination angles at the atmospheric pressure in the water pool. The temperature data were read from the six K-type thermocouples for the bulk fluid utilizing the computer based data acquisition system mainframe of HP VXI-E8406A functioned with the module of HP-1413C. The saturated condition of water was precisely controlled in the vacuum with two temperature controllers. Temperature data readings were taken 10 times per second, and information was filed to a text file by the HP-VEE 5.0 measurement software.



(a) top view



(b) front view

Fig. 4. GAMMA 1D vacuum water pool

IV. RESULTS AND DISCUSSION

This study is concerned with investigation of the CHF accounting for the aspect ratio as well as the gap size and surface orientation effects in the rectangular narrow long channel.

Generally, the bubble behavior in the narrow gap plays an important role in triggering the CHF. The CHF in pool boiling with an open periphery is greater than in the gap boiling because the bubble in the pool boiling is free to escape in the azimuthal direction. Thus, the CHF decreases if it is not easy for the bubble to escape from the heated surface. The gap size, surface orientation and aspect ratio all affect the bubble escaping from the heated surface.

Figure 5 presents the boiling curve for the confined rectangular channel with surface orientation angle from vertical (90°) to downward facing (180°) location. A wavy liquid-vapor interface that sweeps along the heater surface increases the heat transfer in the near-vertical region (90°, 120° and 150°). In particular, the heat transfer at the vertical position (90°) is greater than at other inclinations, as is generally believed, because the buoyant force and the flow direction in the channel are the same so that the mass flux and, accordingly, the CHF increase. On the other hand, the buoyant force repeatedly stratifies the vapor on the heated surface in the rectangular channel at the downward facing position (180°) and further decreases the CHF as captured in Figure 5.

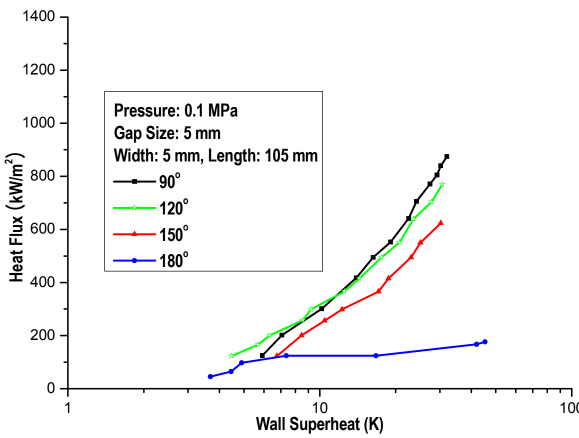


Fig. 5. Boiling curves for gap size of 5 mm

Figures 6 and 7 present the boiling curves compared with the previous experiment having the heated surface of 15×35 mm² at vertical (90°) and downward facing (180°) location, respectively.

As shown in Figure 6, heat transfer is greater than in the previous experiment by the wall superheat (ΔT_{sat}), which is about 20 K at the vertical location (90°). As the heat flux increases, the bubble growth and coalescence are interrupted by the confined channel geometry. Albeit the heated areas are the same between the current and previous heaters, the width is decreased from the previous one, while the length is increased. The aspect ratio of the test heater area to flow area is considerably larger in this study. Specifically, the aspect ratio of the current heater is 21 versus 7 in the previous test heater. Therefore the CHF decreases from the previous heater.

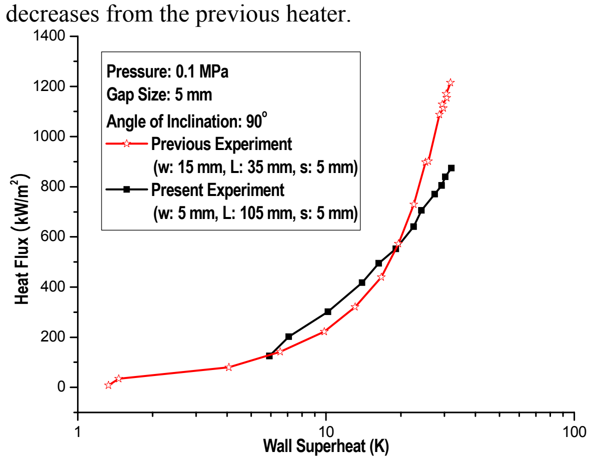


Fig. 6. Comparison of boiling curve for vertical location (90°)

The bubble formed in the gap that is smaller than its own thickness (7~8 mm) is affected by the induced flow effect due to the gap structure at the fully downward facing angle[23]. For the 5 mm width, however, the width is so small that the bubble thickness increases at the downward facing angle. Thus, the induced flow effect increases further in the confined channel. However, the aspect ratio effect is predominant, as shown in Figure 7, because heat transfer is worse than in the previous experiment. Therefore, the CHF for flow area of 75 mm² is greater than that for 25 mm².

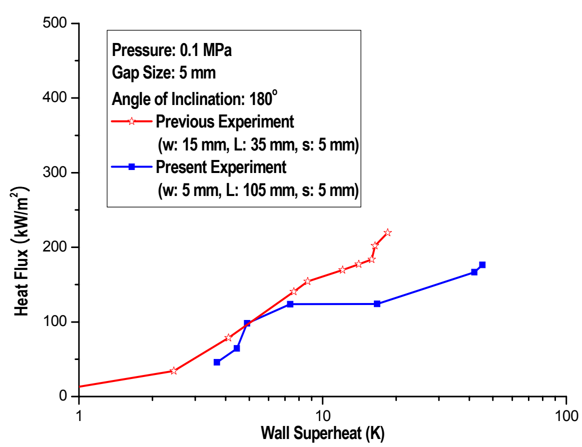


Fig. 7. Comparison of boiling curve for downward facing location (180°)

Figure 8 reveals that the overall CHF in this study is less than that of the previous study with surface orientation angle for the same gap size of 5 mm. The flow rate depends on balance between the driving force and pressure drop in the channel. Given the same gap size, the driving force for the small flow area of 25 mm^2 is greater than that for the large flow area of 75 mm^2 due to high void fraction within the confined channel. Given the flow rate, the pressure drop for the small flow area exceeds that for the large flow area. Therefore, the mass flux for the flow area of 25 mm^2 can go beyond that for the flow area of 75 mm^2 owing to the smaller flow area. Consequently, the CHF for the flow area of 25 mm^2 may be higher than that for the flow area of 75 mm^2.

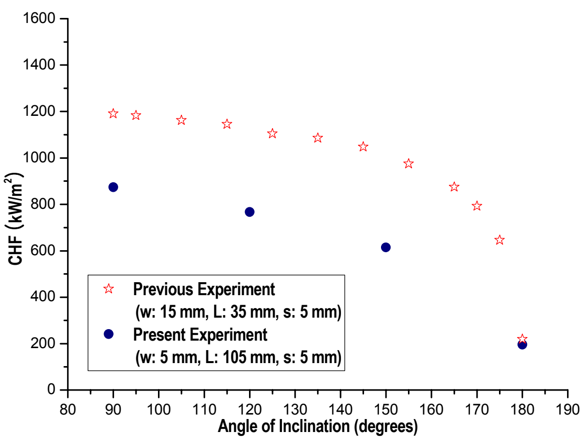


Fig. 8. Comparison against the previous study for CHF

In this study, however, the heated length is greater than the width, and the bubble takes longer time to escape from the heated surface. The friction factor increase, because the aspect ratio is larger than for the heater with the flow area of 75 mm^2 owing to the relatively small width. In other words, the heated length in the heated area of the previous test heater is shorter than that for this study, and hence the aspect ratio is small. Thus, the CHF for the large flow area is greater than that for the small flow area within the surface orientation from vertical (90^o) to downward facing location (180^o) in Figure 8.

Several investigators have recently reported on the existence of a transition angle at which the CHF changes with a rapid slope. The boundary between the near vertical and downward facing regions is generally defined as the transition angle. Existence of the transition angle was discernible as depicted in Figure 9. The distinct transition angles were observed to be 170^o and 150^o for the aspect ratios of 7 and 21, respectively. However, this suggests a good possibility for the transition angle to surpass 150^o in this study. Therefore, there is a need to expand the CHF data between the surface orientation angles of 150^o and 180^o to obtain a precise transition angle.

Figure 10 indicates that the Katto et al. and Kim and Suh correlations[18,23] overestimate the CHF in this study. Even though the Monde et al. correlation[19] underestimates the CHF, their correlation best approximates the CHF in this experiment. This is because Monde et al.[19] had used the ratio of the heated length to the gap size in lieu of the equivalent heated surface diameter to the gap size in the Kim and Suh correlation[23].

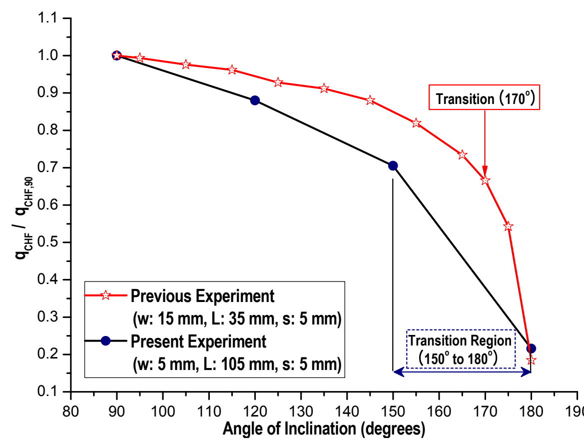


Fig. 9. Comparison with the previous study for surface orientation effect

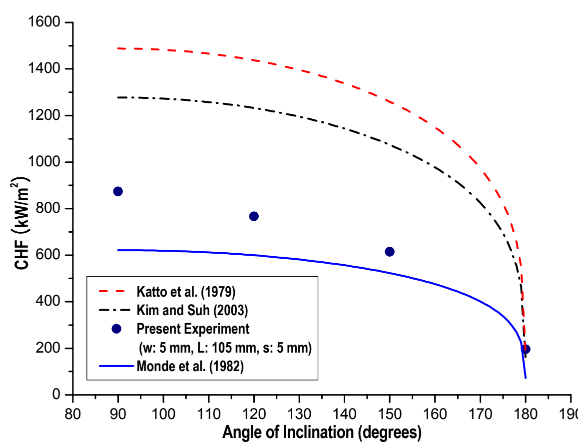


Fig. 10. Comparison of the present study with others for CHF

Figure 11 compares the current data with the Monde et al. correlation[19] for the 1, 2, 5 and 10 mm gaps. It was found that the Monde et al. correlation[19] approximates the CHF in this experiment better than others. The CHF for the 5 mm gap with the surface orientation is enveloped by the

CHF predicted by the Monde et al. correlation[19] for the 5 mm and 10 mm gaps.

V. CONCLUSIONS

In this study, the CHF experiments for gap boiling were performed with the gap size of 5 mm and the surface orientations spanning 90° to 180° at atmospheric pressure utilizing the confined and rectangular narrow long channel. The following conclusions may be drawn.

1. The CHF is affected by the aspect ratio. In other words, the CHF decreases as the aspect ratio of the test heater area to flow area increases.
2. For the same gap size, the transition angle is expected to decrease as the aspect ratio increases due to mass flux and buoyancy.
3. The Monde et al. correlation using the aspect ratio of the heated length to the gap size best approximates the CHF in the study.

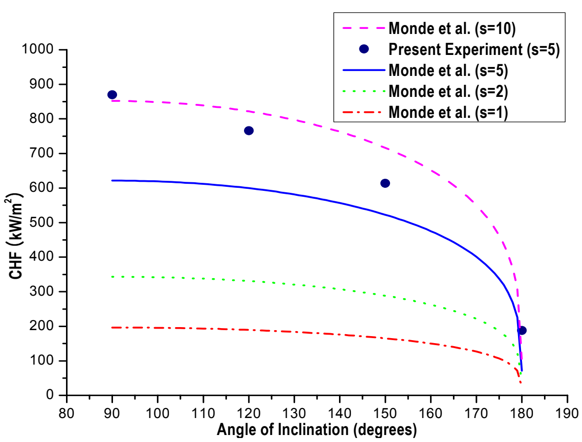


Fig. 11. Comparison of present study with Monde et al. correlation for varying gaps

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NOMENCLATURE

b	length of slot	[m]
C_{CHF}	pool boiling CHF orientation coefficient used by El-Genk and Guo[8]	
D_e	equivalent diameter	[m]
d	disk diameter	[m]
f	friction factor	
g_c	gravitational acceleration	[m/s^2]
h_{fg}	latent heat of vaporization	[J/kg]
k	thermal conductivity	[W/m K]
l	heater length	[m]
q	heat flux	[kW/m^2]
$q_{CHF,0}$	CHF in ordinary pool boiling on upward facing poison (0°)	[kW/m^2]
$q_{CHF,90}$	CHF in ordinary pool boiling on vertical poison (90°)	[kW/m^2]
q_c^*	CHF in ordinary pool boiling on an open heated surface	[kW/m^2]
ΔT_{sat}	wall superheat	[K]
s	channel gap size	[m]
w	channel width size	[m]

Greek Letters

ρ	density	[kg/m^3]
σ	surface tension	[N/m]
θ	surface orientation angle	[deg]

Subscripts

f	saturated liquid
g	saturated vapor

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